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Evaluation of MEMS Structures with Directional Characteristics Based on FRAT and Lifting Wavelet

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Abstract

Steps and grooves, which have typical directional characteristic, are two main functional structures of MEMS (Micro-Electro-Mechanical Systems). This paper proposes a method for analysis and evaluation of MEMS steps and grooves based on finite radon transform (FRAT) and lifting wavelet. The method consists of three steps. Firstly, FRAT is adopted to detect the directional characteristic of a MEMS structure. Secondly, on the basis of the directional characteristic obtained, the profiles of the MEMS structure are analyzed by lifting wavelet. Finally, Histogram-fitting is employed for areal evaluation of a MEMS structure. Simulated and experimental results show that MEMS structures with directional characteristic can be extracted and evaluated by the method effectively.

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Keywords: Directional characteristic; Finite Radon Transform; Lifting wavelet; MEMS structure

1. Introduction

With the rapid development of MEMS (Micro-Electro-Mechanical Systems) technology in recent years, it has been widely used in various industries [1-3]. A sufficient geometric accuracy is the basis to achieve MEMS' functions and interchange ability [4-6]. Micro-steps and grooves are the most widely used structures in MEMS because of their good performances, and currently their geometric accuracy mainly depends on the processing technology [7,8]. With the expansion of application areas of MEMS devices, the micro-steps and grooves have became more and more complex with multi-direction characteristic instead of single direction. Different results will be obtained if the micro-structures are characterized in different directions even by the same parameters. Thereby, accurate extraction of MEMS structures with direction characteristic such as micro-steps and grooves is the basis of their analyses and characterization.

Extraction of direction characteristic is often carried out in image processing. Methods such as steps technique [ref], differential method [9-11], hough transform [12,13] and radon transform [14] are commonly used to deal with it. Steps technique mainly include method of first-order differential and second-order differential which extract directional characteristics by solving extreme values or zero crossing points of first-order and second-order derivative. Differential method gains directional characteristic by convolution between classical differential operators and gray value of image [15]. However, steps technique and differential method have their shortcomings: be too sensitive to the variation of direction and there's too much redundancy in direction characteristic. Various algorithms emerged for extraction of liner characteristic since hough transform was proposed in 1962. However, hough transform is too sensitive to perturbations and is easy to lose information in the transformation process [12,13].

Since radon transform was proposed in 1917 by John Radon, a mass of computing methods were presented by researchers in different fields, but application of them was limited due to lack of inverse transformation for digital surface or image [14,16]. Finite radon transform (FRAT) was proposed in [16,17]. It has the strong ability to extract the

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direction characteristic of a MEMS structure, and reconstruct the MEMS structure with its inverse transformation.

Wavelet transform is a mathematical tool which has been widely used in many fields such as signal analysis, image processing and machine vision, etc. The disadvantages of traditional wavelet transform based on convolution are mass of calculation, high computational complexity and large storage space cost. Lifting wavelet is a more efficient method than wavelets transform which does not depend on Fourier Transform [7]. Application of lifting wavelet to profile picking-up can obtain the profile parameters quickly and accurately with relatively simple algorithm.

This paper proposes a method to extract and evaluate MEMS microstructures with directional characteristic based on FRAT and lifting wavelet transform. 2D and 3D parameters including direction, position, width, height and side wall parameters of the microstructures can be obtained by this method, which formed a relatively comprehensive evaluation system of MEMS.

2. Implementations and examples

2.1. Radon Transform

Radon transform can transform original data matrix into another parameter domain by line integral. The function form of radon transform is written as Eq.(1) [14].

$$Rf(x,y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f(x,y)\delta(p-x\sin\theta+y\cos\theta)dxdy=P_f(\rho,\theta) \tag{1}$$

Where, δ is the sampling function which indicates that $f(x,y)$ takes sampling along θ direction.

2.2. Finite radon transform

Finite radon transform (FRAT) is the radon transform defined in a finite domain.

Defining Z_p as a finite field $Z_p=\{0,1,2,\ldots,p\text{-}1\}$ and p is a prime number. Finite radon transform of real function f on finite grid Z_p^2 is defined as Eq. (2) [8].

$$\begin{aligned}FRAT_f(k,l)=r_k[l]&=\frac{1}{\sqrt{p}}\sum_{(i,j)\in L_{k,l}}f[i,j]\\&=\frac{1}{\sqrt{p}}\sum_{(i,j)\in Z_p^2}f[i,j]\,\delta_{L_{k,l}}[i,j]=\left\langle f,\frac{1}{\sqrt{p}}\delta_{L_{k,l}}\right\rangle\end{aligned} \tag{2}$$

Where, $L_{k,l}$ is a point set on the same straight line whose slope is k and intercept is l defined on the finite grid Z_p^2. There are p+1 straight lines in the set and each line contains p points. For 3D surface data, the size of output result matrix is $(p+1)\times p$ when the input data matrix is $p\times p$. Number of a row in the result matrix (total of p rows) indicates the position (that is intercept) of a directional straight line in original matrix. And every column (p_x) of result matrix (total of p+1columns) corresponds to the dip angle (θ) of texture direction. The corresponding relation is expressed as Eq.(3).

$$\theta=\frac{180}{p+1}*(p_x-1) \tag{3}$$

Because the size of input matrix must be prime number, we need extend the size of original surface data matrix of MEMS to a prime number. When the result matrix is shown in image, the main directional characteristics of a MEMS structure will be shown by highlighted short straight lines. We can get the directions, positions and width of MEMS grooves steps and grooves from the highlighted parts of result matrix.

2.3. Lifting Wavelet

Daubechies and Swelden put forward the entire structure of lifting wavelet in 1997 [7-9]. The basic idea of lifting wavelet is that the difference between two datasets is rather small compare to the dataset itself due to the autocorrelation of dataset itself, so we can use the adjacent data to predict a data. The lifting process can be divided into three parts: splitting, prediction and updating [9-11].

At the splitting stage, the original surface topographical signal $z(x,y)$ is assumed to be $A_j(x,y)=z(x,y)$, $j\in Z$. $A_j(x,y)$ is split into two parts: the odd subset $A_{j,2k+1}$ and the even subset $A_{j,2k}$. Each subset contains half examples of original signal. The operator can be assumed by Eq.(4)[18].

$$\begin{cases}a_{j+1,k}:=A_{j,2k}\\d_{j+1,k}:=A_{j,2k+1}\end{cases} \tag{4}$$

Where, $a_{j+1,k}$ is a sequence of scalar coefficients and $d_{j+1,k}$ is a sequence of wavelet coefficients.

At the prediction stage, we can predict the odd sequence by the even sequence because the correlation of structure on machining surface and get a predict sequence. Then remove the predict sequence from the even sequence, we gain the new odd sequence as shown in Eq. (5).

$$d_{j+1,k}=A_{j,2k+1}-P(A_{j,2k}) \tag{5}$$

Where, P is the prediction factor.

At the updating stage, using the predicted odd sequence to replace the original even sequence, so we can obtain a new signal. In order to make the new signal keep similar properties (e.g. mean value) of original data sequence, we need use an updating factor U to compensate the predicted odd sequence $d_{j+1,k}$ as Eq.(6).

$$a_{j+1,k}=A_{j,2k}+U(d_{j+1,k}) \tag{6}$$

The result $a_{j+1,k}$ is the signal to be processed at the next level in the same steps shown above. The reconstruction of lifting wavelet can be treated as the inverse of lifting process, which means that stages of reconstruction and lifting are in reverse order and exchange the "+" and "-" in the formulas of each step. The three steps above are implemented to $a_{j+1,k}$ again, then after a certain number of iterations later, a multilevel decomposition of the original signal is obtained. The lifting and reconstruct process of lifting wavelet are shown as follow [12].

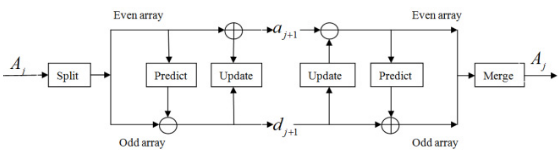


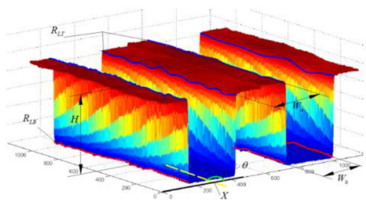
Fig. 1 Lifting wavelet schema

Lifting wavelet has many excellent properties, such as construction of wavelet is performed in time domain and does not rely on the Fourier transform, simple structure and low computational complexity, in-place computing and low storage requirement. This paper uses lifting wavelet as analyzing tool of a MEMS structure to get the profile and roughness parameters.

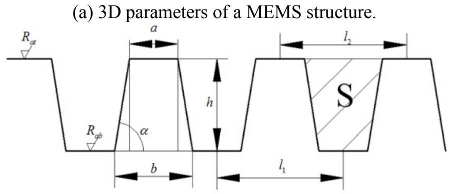
3. MEMS structure parameter evaluation

Up to present, there is no uniform standard for analysis and evaluation of MEMS micro-structures with directional characteristic. This paper presents a series of parameters for evaluation of MEMS micro-structures, such as direction, position, height and width of grooves, dip angles of side wall, sectional area, roughness of step surface and grooves edges. The definitions of parameters are shown in Fig.2, where Fig.2 (a) shows the 3D parameters and Fig.2 (b) shows the 2D parameters of profiles of MEMS grooves.

W_a, W_b are the width of top and bottom of MEMS grooves, H is the height of grooves,θ is the angle of grooves, $X(Y)$ are the positions of grooves or the locations of intersections of grooves and axes on X(Y) axis, R_{LT}, R_{LB} are roughness of top and bottom surfaces of grooves respectively. For parameters of profiles, a is the top width of sectional steps, b is the bottom width of sectional grooves, h is height of sectional steps, l_1 is the centre distance of steps, l_2 is the centre distance of grooves,α is dip angle of side wall, S is section area, Ra is roughness of steps and grooves surface.



(a) 3D parameters of a MEMS structure.



(b) Parameters of 2D grooves profiles

Fig. 2 Parameters of MEMS grooves

In order to obtain the parameters shown above, we need to do FRAT on original data matrix firstly. We can get the direction angles θ, positions of grooves $X(Y)$, width of steps and grooves W_a, W_b and centre distances of grooves l from the FRAT result.

The common analysis methods of microstructure steps are point to point height extraction method, evaluation method based on ISO and NIST standards, least square method and histogram method [13]. By comparison, histogram method can quickly and easily get the height of steps with small error. The principle of histogram is shown in Fig. 3. The figure on the right is the statistical chart of the steps in left figure, where, Z is the actual height value of steps and p is the radio of a high value. p_1 and p_2 are the largest and second largest proportions of statistical probability of step height value, which correspond with the actual top and bottom height of grooves Z_1 and Z_2. The difference value of Z_1 and Z_2 is height of steps H. We can take surface of Z_1 and Z_2 height as the top and bottom surface, so the denoisied ideal MEMS steps surface can use histogram fitting.

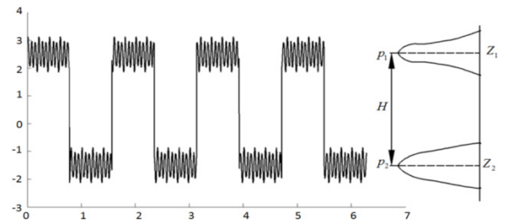


Fig. 3 Principle of Histogram analyses of steps

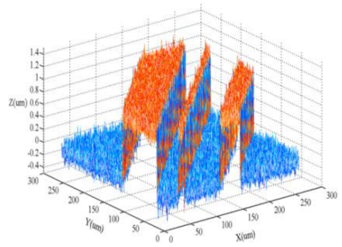
According to the directional angles θ, intercepting the original surface perpendicular to direction with angle of θ, we can get 2D section of MEMS grooves on a special position. Lifting wavelet analysis is carried out on the 2D section data, we can get the profile and roughness (Rat) of the section. The profile is analyzed using histogram method too and we can obtain the denoisied fitting profile of steps. Parameters of 2D profiles (such as a, b, h, S and α can be calculated by the fitting profiles data. Intercepting the original surface along the grooves, we can gain data array of 2D section. The parameters of 2D profiles can reflect morphology of section on a position and validate the correctness of calculation results of 3D parameters. We can calculate the parameter R_{ab} by performing lifting wavelet analysis on the data array. It is difficult to evaluate the side wall of MEMS grooves directly. This paper uses the roughness of line to replace the roughness of surface, which means that the roughness of intersecting lines along the groove by side wall and fitting step top or bottom plane can be seen as the component of roughness of side wall. So, roughness of groove's side wall can be reflected by the roughness of trace contour of steps and grooves surface (that are R_{LT} and R_{LB})

4. Experimental results

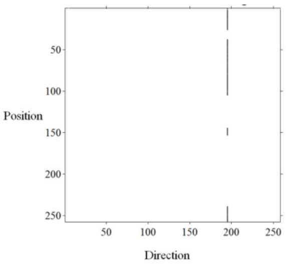
Experiments have been conducted on simulated data and measured data of MEMS steps and grooves.

4.1. Numerical Simulations

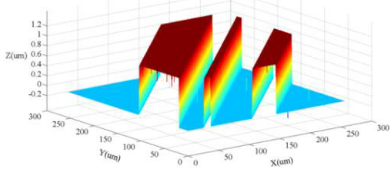
As shown in Fig. 4, the reference angle between the simulated MEMS grooves and the negative of X-axis is 135°, and the projection coordinates of intersections of grooves and X-axis and the surface edge that parallel to the X-axis on the X-axis are 27-37, 106-144 and 153-236. The signal of the structure is mixed in random noise with standard deviation of 0.01. Structure analysis processes consist of FRAT, histogram analysis and lifting wavelet analysis on sections. From the FRAT result, we can gain the direction, position, width, and distance parameters. The height of grooves can be calculated by the result of histogram. According to the result of lifting wavelet analysis performed on the sections perpendicular to grooves, we can gain the extracted profiles and 2D parameters of section.



(a) Simulated data of a MEMS structure



(b) FRAT result of simulated structure



(c) Histogram of simulated MEMS grooves

Fig. 4 Analysis and evaluation of simulated structure

Comparison of calculated parameters and standard values as shown in Tab. 1. As we can see from Tab. 1, the errors of parameters value are all fewer than 4%, which suggests that the analysis and evaluation of simulated data is accurate and effective.

Tab. 1 Comparison of calculated value and standard value of parameters

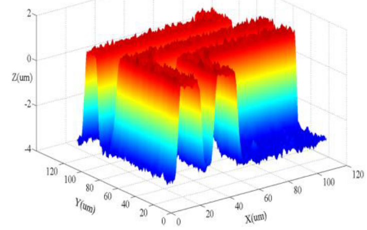
Parameter	W_a			W_b		H	θ	X		
Standard value	59	7	27	31	47	1.0	135°	27-37	106-144	153-236
Calculated value	59.39	7.28	26.87	31.11	47.38	0.9994	135.34°	27-37	106-144	154-238
Error	0.66%	4%	3.2%	3.5%	0.81%	0.06%	0.25%	0%	0%	2.4%

Parameter	S			R_{LT}	R_{LB}	R_{at}	R_{ab}	h
Standard value	42	7	19.09	0	0	0.094	0.094	1.0
Calculated value	43.13	6.82	19.05	0	0	0.091	0.092	0.9994
Error	2.9%	2.6%	2.1%	0%	0%	3.2%	2.1%	0.06%

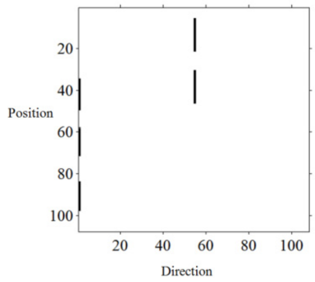
Parameter	a			b		l_1		l_2		α					
Standard value	59	7	27	31	47	46.5	46.5	46.5	46.5	90	90	90	90	90	90
Calculated value	59.39	7.28	26.87	31.11	47.38	46.5	46.5	46.5	46.5	89.55	89.55	89.55	89.55	89.55	89.55
Error	0.66%	4%	3.2%	3.5%	0.81%	0%	0%	0%	0%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%

4.2. Experiments with measured data

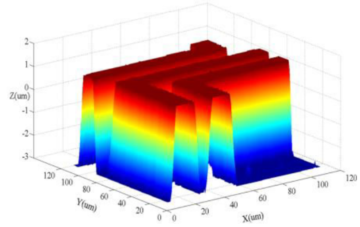
The measured MEMS microstructure shown in Fig. 5 has three steps in two directions. The analysis method used here is similar to the simulated structure. The analysis and evaluation results are shown in Fig. 5 and Tab. 2.



(a) Measured MEMS grooves



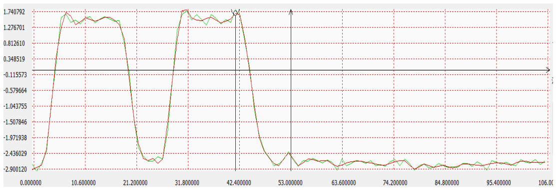
(b) FRAT result of measured MEMS grooves



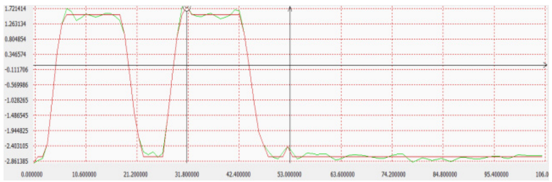
(c) Fitted surface gained by histogram analysis of measured MEMS grooves

(d) Lifting wavelet analysis of section on position X = 60 in vertical direction (the green curve is original section and the red curve is extracted profile)

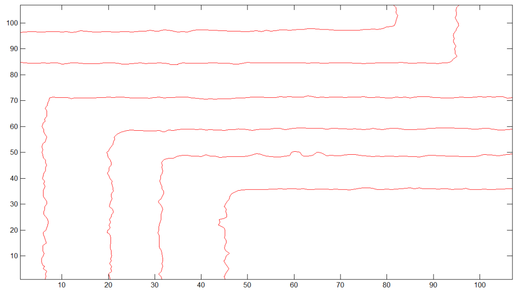
(e) Histogram analysis of profile on position X = 60 in horizontal direction (the green curve is original profile and the red curve is fitting curve by histogram



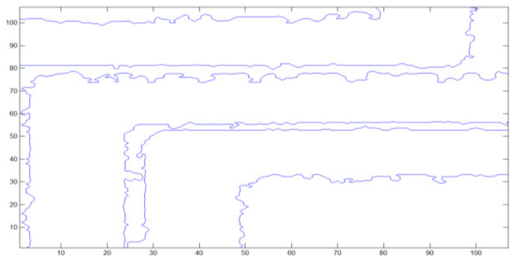
(f) Lifting wavelet analysis of section on position Y = 20 in vertical direction (the green curve is original section and the red curve is extracted profile)



(g) Histogram analysis of profile on position Y = 20 in vertical direction (the green curve is original profile and the red curve is fitting curve by histogram)



(h) Roughness curve of the grooves top



(i) Roughness curve of the grooves bottom

Fig. 5 Analysis and evaluation of measured MEMS structure

Tab. 2 Calculated values of parameters of measured MEMS structure

Parameter	W_a			W_b		H	θ		X		
Calculated value	15	14	14	9	12	4.1	0°	90°	7-19	32-44	82-95

Parameter	R_{ab}	S		R_{LT}	R_{LB}	R_{at}	Y		
Calculated value	0.204	38.95	68.68	0.244	0.252	0.188	37-48	59-71	85-96

Parameter	a			b		h	l_1		l_2		α					
Calculated value	14	12	12	7	10	4.1	25	50.5	18	26	86.65	85.82	86.65	84.99	85.82	87.49

It can be seen from Fig. 5 that the FRAT result can accurately reflect the directions and positions of the MEMS micro-structures. The fitted surface and curves can show the standard grooves' appearances of original grooves. Values of 2D parameters and 3D parameters are mutually authenticated well. The evaluation of measured MEMS structure is effective and accurate.

5. Conclusion

This paper explored a method for extracting and evaluating MEMS structures with directional characteristic such as steps and grooves, based on FRAT and lifting wavelet, where FRAT is employed to extract the directional characteristic of a MEMS structure, and then lifting wavelet is used to analyze the profiles of the MEMS structure. Finally, Histogram analysis is employed for areal evaluation of a MEMS structure. Simulated and Experimental results proved the effectiveness of this method.

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